UCRL-ID-133629

Chamber and Target Technology Development for Inertial Fusion Energy

R.W. Meier, B.G. Logan, J.F. Latkowski, R.W. Moir, S.A. Payne,
G. Besenbruch, D. Goodin, K. Schultz, J. Duke, L. Forman,
W. Steckle, J. Hoffer, B. Margevicius, A. Nobile, P.F. Peterson,
R. Petzoldt, M. Abdou, N. Morley, A. Ying, K. Gulec,
M.S. Tillack, I.N. Sviatoslavsky, G.L. Kulcinski, R.R. Peterson, H.Y. Khater

April 7, 1999

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

Chamber and Target Technology Development for Inertial Fusion Energy

Lawrence Livermore National Laboratory
W.R. Meier, B.G. Logan
J.F. Latkowski, R.W Moir, S.A. Payne

General Atomics
G. Besenbruch, D. Goodin, K. Schultz

Los Alamos National Laboratory
J. Duke, L. Forman, W. Steckle, J. Hoffer, B. Margevicius, A. Nobile

University of California, Berkeley
P.F. Peterson, R. Petzoldt

University of California, Los Angeles
M. Abdou, N. Morley, A. Ying, K. Gulec

University of California, San Diego
M.S. Tillack

University of Wisconsin
I.N. Sviatoslavsky, G.L. Kulcinski, R.R. Peterson, H.Y. Khater

April 7, 1999

Contents

List of Tables

List of Figures

1. Introduction

Fusion chambers and high pulse-rate target systems for inertial fusion energy (IFE) must:

- regenerate chamber conditions suitable for target injection, laser propagation, and ignition at rates of 5 to 10 Hz,
- extract fusion energy at temperatures high enough for efficient conversion to electricity,
- breed tritium and fuel targets with minimum tritium inventory,
- manufacture targets at low cost,
- inject those targets with sufficient accuracy for high energy gain,
- assure adequate lifetime of the chamber and beam interface (final optics),
- minimize radioactive waste levels and annual volumes, and
- minimize radiation releases under normal operating and accident conditions.

The primary goal of the US IFE program over the next four years (Phase I) is to develop the basis for a Proof-of-Performance-level driver and target chamber called the Integrated Research Experiment (IRE). The IRE will explore beam transport and focusing through prototypical chamber environment and will intercept surrogate targets at high pulse rep-rate. The IRE will not have enough driver energy to ignite targets, and it will be a non-nuclear facility. IRE options are being developed for both heavy ion and laser driven IFE. Fig. 1 shows that Phase I is prerequisite to an IRE, and the IRE plus NIF (Phase II) is prerequisite to a high-pulse rate Engineering Test Facility and DEMO for IFE, leading to an attractive fusion power plant. This report deals with the Phase-I R&D needs for the chamber, driver/chamber interface (i.e., magnets for accelerators and optics for lasers), target fabrication, and target injection; it is meant to be part of a more comprehensive IFE development plan which will include driver technology and target design R&D.

Because of limited R&D funds, especially in Phase I, it is not possible to address the critical issues for all possible chamber and target technology options for heavy ion or laser fusion. On the other hand, there is risk in addressing only one approach to each technology option. Therefore, in the following description of these specific feasibility issues, we try to strike a balance between narrowing the range of recommended R&D options to minimize cost, and keeping enough R&D options to minimize risk.

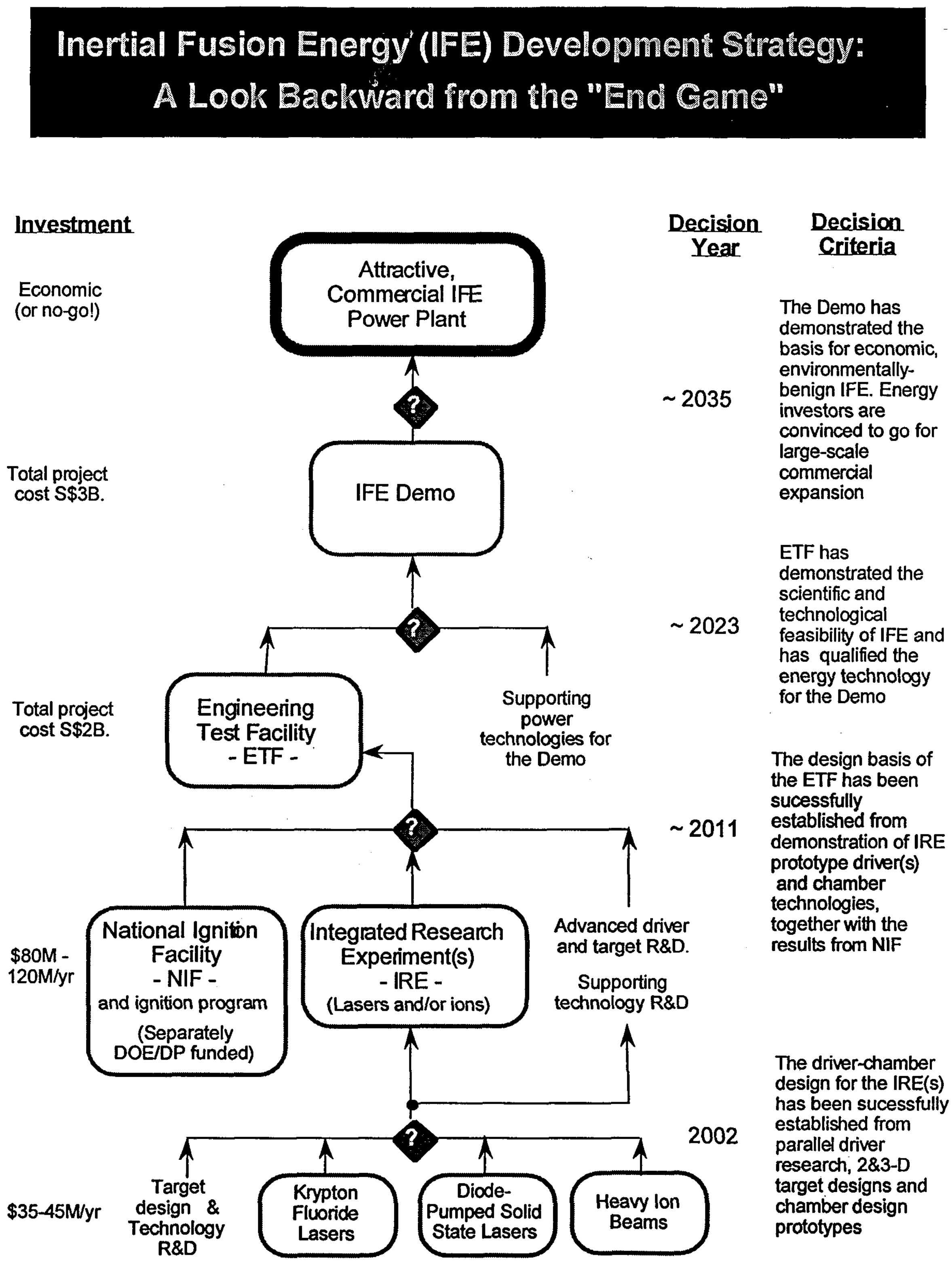

Fig. 1. A phased, criteria-driven IFE development strategy.

II. Heavy-Ion Fusion Chambers

Heavy-ion fusion (HIF) is possible in principle using a wide variety of targets and chambers, including direct-drive, indirect-drive, and fast-ignition targets, and dry-wall, wetted-wall, and thick-liquid-wall chamber concepts. However, the most likely potential for HIF would be realized with a particular combination of indirect-drive target geometry (possibly including future enhancements of single-ended beam illumination and fast ignition), and with liquid protected chambers (possibly including wetted-wall concepts with minimum blanket structure needing periodic replacement), because of the following reasons:

1. recent success and higher-than-adequate energy gain of close-coupled indirect-drive hohlraum designs for HIF based on LASNEX calculations, and the possibility of NIF testing most of the critical target capsule and hohlraum symmetry requirements;
2. simplified beam transport and final focusing of energetic ion beams between the accelerator and chamber made possible with two-sided beam illumination of targets;
3. tolerance of heavy-ion beams to the vapor pressure of high-temperature lithium-bearing liquid coolants, while being focused through final focus magnet bores and propagated through the chamber, that is, compatibility with liquid-protected chambers;
4. significantly increased lifetime (for thick-liquid concepts), elimination of dangerous solid first wall failure modes, and reduced radioactive waste generation (for both thick-liquid and mostly-liquid wetted-wall concepts); and
5. smaller chamber size.

We have selected thick-liquid wall chambers, such as HYLIFE-II (see Fig. 2), with indirect drive targets as the basis for this R&D plan. While a variety of heavy ion chamber options are potentially viable (e.g., wetted wall designs such as Hiball, Osiris and Prometheus-H), the potential advantages of the thick liquid wall chambers are so compelling, that we have focused our near term R&D on this concept.

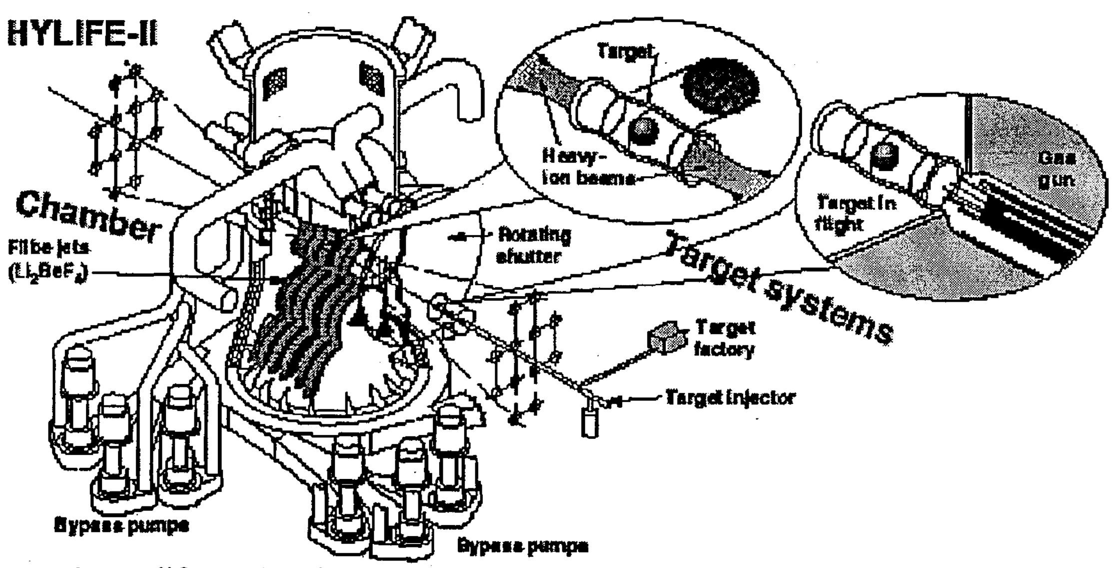

Fig. 2. The Hylife-II chamber is a thick-liquid-wall concept. Flibe jets protect stainless steel structures from direct exposure to the fusion pulse and reduce neutron damage to the point that structures are expected to last for the life of the plant.

II.1 Critical Issues for HIF Chambers

Associated with this vision for HIF power plants are a number of critical chamber issues (Table 1) for which near-term R&D in Phase I must show sufficient feasibility to support the candidacy of HIF for Phase II.

Table 1. Major Feasibility Issues for HIF Chamber Technology

- *Liquid Chamber Clearing.* Basics of liquid-protected chamber clearing feasibility - vapor condensation, droplet clearing, and flow recovery rate for ~5 Hz operation.
- *Final-Focus/Chamber Interface.* Physical accommodation and shielding of final focus magnet arrays consistent with chamber solid-angle limits, required number of beams, magnet dimensions and neutron shielding

II.2 Tasks and Costs for HIF Chamber R&D

Table 2 lists the Phase-I tasks and estimated costs for HIF chamber R&D. (Phase-I Tasks for Laser Chambers, Safety and Environmental, and Target Technology (fabrication, injection and tracking) are listed in Sections III, IV, and V, respectively).

Table 2. Tasks and Costs for HIF Chamber R&D*

Area / Task	FY00 ($K)	FY01 ($K)	FY02 ($K)	Lead / Support (fraction of total)
1.0 HIF Chamber R&D	*1800*	*1800*	*1800*	
1.1 Liquid Jet Hydraulics	*450*	*275*	*275*	
1.1.1 Free Jet Formation	250	75	75	FY00: UCB(0.35) / UCLA(0.35 / GT(0.3) FY01-02: GT(1.0)
1.1.2 Vortices and Wetted Walls	200	200	200	UCLA
1.2 Liquid Shock Response	*250*	*425*	*425*	
1.2.1 Shocks and Droplet Clearing	150	325	325	UCB(0.67) / INEL(0.33)
1.2.2 High-Strain-Rate Liquid Response	100	100	100	UCLA
1.3 Plasma/Vapor Condensation	*350*	*350*	*350*	
1.3.1 Superheated Vapor Condensation	200	200	200	
1.3.2 Diagnostics Development	50	50	50	
1.3.3 Shock Interaction with Structures	100	100	100	UW
1.4 Design, Modeling and System Studies	*470*	*470*	*470*	LLNL(0.5) / UCB(0.25) UCLA(0.25)
1.5 Additional Studies	*280*	*280*	*280*	
1.5.1 Final Focus Magnet Shielding	60	60	60	LLNL
1.5.2 Flibe Chem, Tritium, Hohlraum Matl.	200	200	200	ANL(0.8) / LANL(0.2)
1.5.3 HIF-Target X-ray/Debris Calcs	20	20	20	

*Please note:
This draft plan indicates institutions that have stated their willingness to
a) coordinate their potential work in IFE with the Virtual Lab for Technology on the indicated tasks, and
b) submit proposals to DOE for the indicated tasks.
This draft plan does not legally obligate DOE to fund any of these tasks or institutions.
This draft plan does not exclude any institution from submitting proposals for any task to DOE.

II.3 Phase-I Deliverables for HIF Chamber R&D

Phase-I deliverables related to the key issues are summarized below.

- *Liquid Chamber Clearing.* Clearing demonstrated with properly scaled model liquid experiment, including simulated target blast forces.

- *Final-Focus/Chamber Interface.* Self-consistent magnet/chamber designs that simultaneously accommodate the size of final focus magnets, shielding, and the necessary placement to hit a ~ 3 mm radius spot.

II.4 Summary Description of HIF Chamber Tasks for Phase-I

The Phase-I studies take advantage of the modularity of liquid-jet pockets by performing experiments with single scaled jets and clusters of a few jets, allowing extrapolation to the much larger flow and power levels that will be required in Phase-II experiments. Phase-I experiments also take advantage of the large differences in time scales of groups of phenomena, separating studies of slow liquid hydraulic response from studies of rapid ablation and venting phenomena. Tasks are listed by work breakdown structure (WBS) number given in Table 2.

1. Heavy-Ion Fusion Chamber R&D ($1800 K/y)

1.1 Stationary and Oscillating Liquid Jet Hydraulics ($450 K/y)

1.1.1 Free Jet Formation ($250 K/y)

These studies focus on single jet experiments to enlarge the market basket of jet geometries available for creating pockets. The efforts will provide optimized nozzle designs for smooth stationary and oscillating rectangular jets, determine their surface roughness and droplet ejection characteristics, investigate more complicated multidimensional jet geometries, and explore methods to introduce voids inside jets to accommodate neutron isochoric heating and mitigate shock propagation. Efforts to maximize the effectiveness of flow conditioning and turbulence suppression, while minimizing pumping power, will be important. Because the goal of jet formation is to avoid spray generation, scaling should match Reynolds (inertia vs. friction) and Weber (inertia vs. surface tension) numbers.

1.1.2 Vortices and Wetted Walls ($200 K/y)

In addition to providing a backup to thick liquid protection, thick vortices and thin-film wetted walls can potentially be useful to protect isolated regions along the beam lines in thick liquid chambers, including forming liquid layers coating the inside surface of beam line penetrations into the target chamber to provide additional magnet shielding. This area is synergistic with MFE liquid-wall research which also concentrates on vortices. IFE emphasis will be on ways to mitigate the effects of pulsed target emissions (neutrons, x-rays and target debris) so that vortex flows can be maintained in steady-state without breakup.

1.2 Liquid Shock Response to Target Explosions and Droplet Clearing ($250 K/y)

1.2.1 Shock Propagation And Droplet Clearing ($150 K/y)

Partial pocket experiments, where a portion of the pocket jet structure is replaced by solid structures, reduce the complexity of the required oscillating nozzle system. In these experiments, the liquid pocket is disrupted by detonation of a fuel-oxidizer mixture inside the pocket or by a shock-tube blast, imparting scaled impulse loading to the liquid. Transient pressure measurements and high-speed photography provide information on shock propagation through the liquid structure and droplet and high-velocity slug formation. Clearing of the volume swept by the subsequent oscillating jet motion is then confirmed by passing laser beams through the swept volume. In scaling these experiments to reduced geometric scale the most important parameters are the Weber (inertia vs. surface tension) and Froude (inertia vs. buoyancy) numbers, which give the correct scaled droplet size and droplet trajectories. For example, scaling the jet velocity by a factor of 1/2 allows matching Froude numbers at 1/4 geometric scale and 1/32 volumetric flow, allowing larger numbers of jets. Jet Reynolds numbers can not be matched but remain turbulent, and with a somewhat larger experimental system, droplet clearing with oscillating arrays of 5 to 10 jets can be studied.

1.2.2 High-Strain-Rate Liquid Response and Fracture ($100 K/y)

Fundamental experimental data is to be obtained on high strain rate liquid fracture using non-neutron-induced shocks in liquids driven by a small laser. Computational modeling of the behavior of shocks and rarefaction waves driven into liquid structures in the experiment will be used to predict associated breakup behavior of films and jets.

1.3 Plasma/Vapor Condensation, and Target Debris Clearing ($350 K/y)

X-ray ablation and debris venting occur over time scales of tens of microseconds with complete pocket venting over hundreds of microseconds, and condensation over tens of milliseconds. Ablation and pocket pressurization generate impulse loading on liquid surfaces that must be quantified through experimentally verified numerical simulations, and at small length scales can strip small liquid droplets from liquid surfaces. While condensing surface area can be made arbitrarily large using droplet sprays and heat transfer in the droplet liquid is readily predicted, effects of very high debris superheat and noncondensable gases require further study. Phase I activities provide modeling tools, separate effects experiments and diagnostics development to support Phase II experiments and to address fundamental feasibility issues by demonstrating that impulse loads and condensation rates can be predicted conservatively. Experimental sub-areas are:

1.3.1 High-Velocity Superheated Vapor Condensation ($200 K/y)

Studies of mechanisms for the interaction of shocks with droplet clouds and condensation of highly superheated vapor on droplets. A portfolio of innovative experiments, coupled with model development, is proposed. Experiments can include use of pulsed energy sources to generate plasmas from salt and observation of condensation on surfaces and solid rod banks designed to simulate droplet clouds, possible ride-along experiments in Z-pinch facilities to collect and measure condensed target and ablation debris, and other innovative experiments.

1.3.2 Diagnostics Development for Ablation/Venting/Condensation ($50 K/y)

Efforts to design diagnostics for transient measurements under high EMP loading, for future integrated ablation, venting and condensation tests in NIF and/or Z. (Overlaps with laser-IFE)

1.3.3 Shock Interaction With Solid and Liquid Structures ($100 K/y)

Shock-tube studies of gas dynamics of flow over objects and interactions with liquids, droplet stripping and entrainment, momentum transfer to liquid jets, to support hydrodynamics code benchmarking. (Overlaps with laser fusion.)

1.4 Modeling and System Studies ($470 K/y)

It will be important to integrate the results of the various IFE R&D activities to assure progress toward meeting Phase-I milestones and development of an attractive end product. These studies provide a vital component of the 2002 feasibility assessment by demonstrating integration of all target chamber design issues. The following near-term tasks are focused on these needs:

- Continue planning for IFE chamber/target technology area with focus on objectives, milestones, and deliverables for Phase-I R&D.
- Establish objectives and determine design requirements for future integrated systems in the IFE development plan including the Integrated Research Experiments (IREs), Engineering Test Facility (ETF), and Demonstration Power Plant (Demo). Develop metrics (e.g., cost of electricity for a power plant) for these facilities to aid decision making.
- Develop, improve, and exercise of systems models for IRE, ETF, and Demo including major subsystems (i.e., chambers, drivers, target fabrication).

Tasks specific to liquid wall chambers include:

- Update current liquid-wall conceptual designs to incorporate innovative ideas and new information and modeling capability provided by ongoing experimental and modeling efforts.
- Explore innovations such as directed downward venting to eliminate venting slots in the HYLIFE-II design and shielding approaches to reduce final-focus magnet standoff distance, and the use of axisymmetric cusp focusing magnets with vortex-liquid shields.

Tasks specific to structure lifetime include:

- Develop structural design criteria for IFE components and determine the lifetime of the chamber structure including radiation effects and temperature gradients (Overlaps with MFE activities).

Toward the end of Phase-I, it may be appropriate to conduct a major power plant conceptual design study to account for the progress made not only on chamber and target technologies, but also on the driver technology and target design. The cost of such a study would far exceed the $470 K/y allocated to this area and would require support from the Driver Technology and Target Design elements of the IFE program.

1.5 Additional Studies ($280 K/y)

Three smaller topical areas require study during Phase I. These studies are focused on specific issues, as opposed to the systems studies which explore the relationships and trade-offs in integrated systems. Here considerable overlap exists with MFE, laser fusion, and international fusion research efforts, reducing the investment required from HIF.

1.5.1 Superconducting Magnet Shielding and Thermal Response ($60 K/y)

Computational neutronics studies of focus magnet shielding, experiments for small-angle scattering cross sections, and superconducting magnet thermal design for pulsed heat loading.

1.5.2 Flibe Chemistry, Tritium and Hohlraum-Material Recovery ($200 K/y)

Studies of specific Flibe and hohlraum material thermophysical and chemical properties relevant to IFE coolant use. Flibe experiments to define methods for efficient tritium recovery and effective tritium containment, to contribute to structural material selection, to establish operational limits for proposed structural materials, to identify control and removal methods of coolant impurities (target-debris and corrosion products). (US-Japanese collaboration proposed for Mid FY01, overlaps with laser fusion and MFE.) This area provides data to support the chamber design, and it is closely coordinated with Safety & environmental R&D (see Section IV below for research on oxidative release).

1.5.3 HIF Target X-ray and Debris Emission ($20 K/y)

Efforts to run HIF-Lasnex distributed radiator target designs past ignition time to quantify target debris and x-ray emission and equivalent x-ray black–body spectra, and to investigate the effect of increasing wall thickness on x-ray/debris energy partitioning and spectra. Turbulence during target disassembly makes these calculations labor intensive using Lagrangian methods, so mapping post-ignition results into an Eulerian code may be useful.

III. Laser Fusion Chambers

Laser fusion (LF) is possible in principle using a wide variety of targets and chambers, including direct-drive, indirect-drive, and fast-ignition targets, and dry-wall and wetted-wall chamber concepts. Fast ignition may even allow thick liquid wall chambers. However, the most likely option for laser fusion is currently considered to be direct-drive targets and gas-protected dry-wall chambers. Direct drive targets require uniform illumination by 60 or more beams. The dry-wall chamber, Sombrero (see Fig. 3), has been selected as the point of departure for the near-term chamber R&D work in laser IFE. If development issues with the Sombrero chamber prove insurmountable or if additional funding were available, there are a variety of other laser chamber options that could be included in the R&D plan. The chamber/driver interface is considered part of the chamber technology R&D. Currently, two classes of final optics designs are being considered: 1) grazing incidence metal mirrors (GIMM) with either a metal or liquid metal surface (GILMM), and 2) diffractive optics, using either fused silica wedges or transmission gratings at temperatures of >400 °C to continually anneal radiation damage.

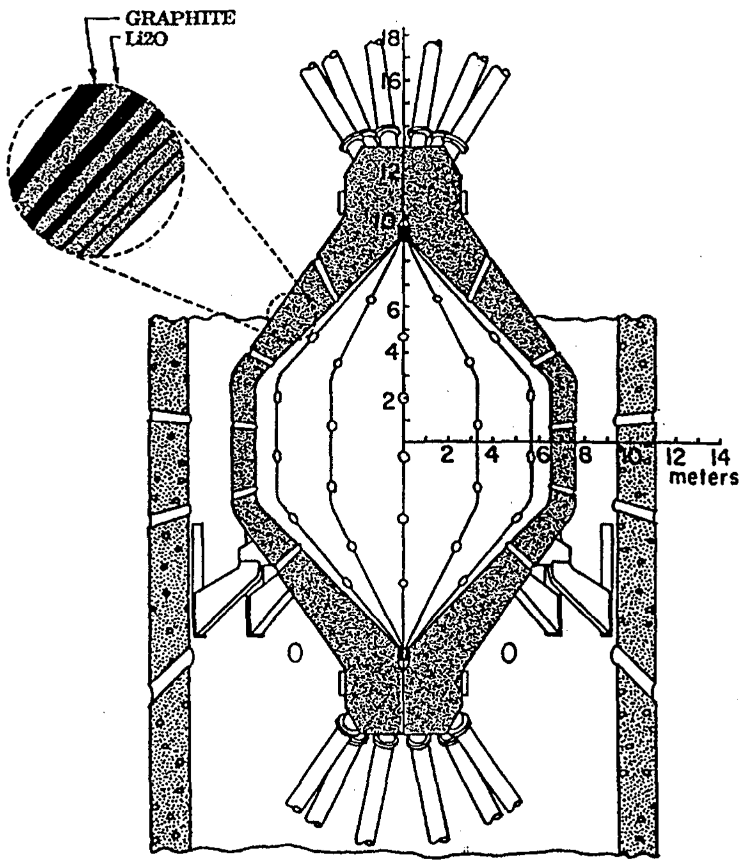

Fig. 3. Side cross-section of the SOMBRERO chamber. The design features a carbon/carbon structure for the first wall and blanket. The first wall is protected from x rays and debris by a 0.5 Torr of xenon gas.

III.1 Critical Issues for Laser Fusion Chambers

The key issues for the chamber and target technologies are summarized in Table 3. They will be discussed in more detail in the following sections along with the R&D plans to address them.

Table 3. Major Feasibility Issues for Laser Fusion Chamber Technology

- *Chamber Lifetime Uncertainty.* X-ray and debris damage to first wall must be prevented; neutron damage life of first wall and blanket structures must be acceptably long, probably at least 1 year depending on replacement time; possible erosion of coolant channels by flowing granular coolant/breeder must be manageable or prevented.

- *Final Optics Design and Survivability.* Damage from laser light, x-rays, and debris must be prevented; neutron damage life must be acceptably long (also likely greater than 1 year); optics must be mechanically stable against gas shocks even after attenuation up the beam line.

III.2 Tasks and Costs for Laser Fusion Chamber R&D

Table 4 lists the Phase-I tasks and estimated costs for laser fusion chamber R&D.

Table 4. Tasks and Costs for Laser Fusion Chamber R&D*

	FY00	FY01	FY02	Lead / Support
Area / Task	($K)	($K)	($K)	(fraction of total)
2.0 Laser Fusion Chamber R&D	*1800*	*1800*	*1800*	
2.1 First Wall/Blanket	*400*	*400*	*400*	
2.1.1 Material Development	100	100	100	
2.1.2 Radiation Damage Studies	150	150	150	UW
2.1.3 Flowing Granular Bed	50	50	50	UW
2.1.4 Tritium Retention	100	100	100	
2.2 Fireballs and Chamber Dynamics	*550*	*550*	*550*	
2.2.1 Fireball Experiments	250	250	250	
2.2.2 Fireball Modeling	250	250	250	UW
2.2.3 Chamber Dynamics	50	50	50	UCSD
2.3 Final Optics Protection R&D	*600*	*600*	*600*	
2.3.1 GIMM Laser/Neutron Damage	150	150	150	UCSD
2.3.2 Fused Silica Laser/Neutron Damage	150	150	150	LLNL
2.3.3 Alternative Final Optic Protection	100	100	100	LLNL(0.8) / ANL(0.2)
2.3.4 Gas Protection / Shock Tube Expts.	100	100	100	UW
2.3.5 RHEPP Expts.	100	100	100	SNL
2.4 Design, Modeling and System Studies	*250*	*250*	*250*	UW(0.7) / LLNL(0.3)

Please note:
This draft plan indicates institutions that have stated their willingness to
a) coordinate their potential work in IFE with the Virtual Lab for Technology on the indicated tasks, and
b) submit proposals to DOE for the indicated tasks.
This draft plan does not legally obligate DOE to fund any of these tasks or institutions.
This draft plan does not exclude any institution from submitting proposals for any task to DOE.

III.3 Phase-I Deliverables for Laser Fusion Chamber R&D

Phase-I deliverables related to the key issues are summarized below.

Chamber Lifetime.

- Reassessment of C-C FW lifetime (neutron irradiation data)
- Experiments to assess effectiveness of gas protection
- Measure erosion rate from granular solid coolants
- Design rapid FW change-out procedures

Final Optics Design and Survivability.

- Extend hot-fused silica neutron irradiation data for DPSSLs
- Test GIMM and GILMM with KrF lasers
- Measure shock effects from anticipated fireballs and propose solutions
- Test effectiveness of xenon gas for x-ray protection

III.4 Summary Description of Laser Fusion Chamber Tasks for Phase-I

In this section, we give a brief description of the tasks listed in Table 4 by work breakdown structure (WBS) number.

2. Laser Fusion Chamber R&D ($1800 K/y)

2.1 First Wall/Blanket ($400 K/y)

2.1.1 Material Development ($100 K/y)

The material used in the SOMBRERO chamber is a rigidized multi-weave (3D or 4D) C/C composite. Such materials are commonly used in the aero-space industry in re-entry vehicles and in complex shapes used in such aircraft as the Stealth bomber. The major difference from the manufacturing standpoint is the size of the components which are quite large in SOMBRERO (26m). Even though C/C composites are known to be very strong, they still need to be tested under heat and impulsive loads at rep-rates on the order of 6-7 Hz. The impulses on the first wall have been determined to be on the order of 2.2 Pa-s with a peak pressure of 1.27×10^{-3} Mpa lasting about 90 microseconds. An important aspect of the first wall is its thermal conductivity, which along with the heat transfer coefficient on the cooled side determine the maximum temperature of the graphite wall.

Thus from a material development standpoint, a program is needed for determining the best graphite for the design and how to engineer it to provide strength under repeated loads of heat and impulses, provide high thermal conductivity, be radiation tolerant, and finally how to manufacture large components such as those needed for SOMBRERO.

2.1.1.1 Selection of C/C Composite ($70 K/y)

Selecting the best C/C composite is the most important aspect in the design of the chamber. Using existing graphites developed for the aero-space industry can be a starting point. Testing of samples under simulated heat and impulse loading would be the first step. Building on what is learned from these tests, a program is needed to develop a graphite C/C composite with the specific ability to withstand neutron damage, have a high thermal conductivity, strength under repeated heat and impulse loading and the ability to be fabricated into large complex shapes.

2.1.1.2 Maximizing Thermal Conductivity ($20 K/y)

It has been shown that C/C composites display preferentially enhanced thermal conductivity depending on the orientation of the fibers in the weave. Thus, finding the proper weave which maximizes the fibers perpendicular to the first wall without compromising the strength of the composite is needed.

2.1.1.3 Leak Tightness ($10 K/y)

The chamber is designed to be capable of tolerating a large number of small pinholes. For example, there can be 10^6 pinholes of 100 microns each, without compromising the operation of the chamber. Nevertheless, testing of capsules that have been irradiated by neutrons and subjected to heat and impulses at the proper rep-rate to determine hermeticity will be needed.

2.1.2 Radiation Damage ($150 K/y)

A protective gas in the SOMBRERO chamber stops the x-rays and ions from impacting the first wall by absorbing the energy and re-radiating it over a longer time scale. Neutrons, however, cannot be stopped and they cause damage in the graphite. Radiation damage by neutrons can limit the lifetime of the chamber by weakening the material, cause excessive swelling, decrease thermal conductivity and possibly cause increased uptake of T_2 by the graphite. It has been assumed that 70 dpa can be tolerated in the SOMBRERO chamber, which is a factor of two higher than available data would predict. Available data predicts that after shrinkage, the graphite returns to its original dimension at about 35-45 dpa, before continuing further swelling. However, the chamber is designed to be capable of accommodating swelling beyond the return to the original dimension limit, because the tolerances on the fit of the chamber are quite large.

2.1.2.1 Mechanical and Physical Properties ($100 K/y)

In the absence of 14 MeV neutron sources, various samples of C/C composites will have to be irradiated in fission reactors as a preliminary screening to determine radiation tolerance. Ultimately, the same will have to be done with fusion neutrons under simulated pulsing which can be done with rotating shielded shutters. Some information is currently available, but will have to be expanded to include other graphites and the tests extended to 70-100 dpa. Post irradiation tests to determine swelling, strength deterioration and decrease in fracture toughness have to be conducted in samples both prior to pulsing and after pulsing. SEM inspection of samples before and after irradiation must be made to determine the changes in the surface characteristics which could determine crack propagation or T_2 uptake.

2.1.2.2 Thermal properties ($50 K/y)

The most critical thermal property for graphite materials is thermal conductivity. This test will determine the degradation in thermal conductivity as a result of radiation damage. Here again, tests will be made before and after pulsing to determine the effect on thermal conductivity of both radiation damage and pulsing. Since thermal conductivity is a function of temperature, these tests will be performed at temperatures relevant to the reaction chamber.

2.1.3 Flowing Granular Bed ($50 K/y)

The chamber in SOMBRERO is cooled with solid particles of Li_2O flowing by gravity through channels made of the C/C composite aided with He gas at 0.2 Mpa. The particle velocity in the front zone is on the order of 1 m/s but slows down to a low velocity of several cm/s in the back. There are several areas that need investigation in such a system, among them heat transfer coefficients, flow control, dust generation and its accumulation on surfaces, breakup of particles, erosion of structural surfaces and particles transport outside the chamber.

2.1.3.1 Physical Aspects of Granular Flow ($30 K/y)

These experiments will test all aspects of flowing granular Li_2O particles with the exception of heat transfer coefficients. A loop will be built with moving bed particulates circulated in a steady state mode, with the capability of controlling the flow velocity and temperature. This loop will address such aspects as physical erosion of C/C composites, as well as particle breakup, dust generation and its accumulation on the first wall inside surface. The experiment will also test various methods of transporting the particles within an atmosphere of 0.2 Mpa to provide a continuous flow for steady state experimentation.

2.1.3.2 Thermal Aspects of Granular Flow ($20 K/y)

The heat transfer coefficient at the first wall plays a major role in determining the temperature of the first wall. There is a large body of information available on flowing solid particle beds with respect to heat transfer. This information must be adapted for the special characteristics of Li_2O particles of the correct size, velocity and temperature, flowing on C/C composite, to verify heat transfer calculations made for the SOMBRERO chamber. This information is only important to the cooling of the first wall, since the remainder of the chamber does not depend on thermal conductivity or heat transfer coefficients (since most of the energy is directly deposited in the Li_2O by neutrons).

2.1.4 Tritium Retention ($100 K/y)

Tritium retention in the structural walls of the chamber must be well known for safety reasons. It is well known that T_2 attaches itself to and permeates graphites at temperatures < 300 °C . However, most of the SOMBRERO chamber operates at temperatures in excess of 600 °C. Furthermore, a minute quantity of water vapor is introduced into the Li_2O stream to convert the T to tritiated water, i.e., HTO. More information is needed to determine the degree to which graphite will uptake HTO at temperatures in excess of 600 °C. Further, no T in the form of ions will reach the first wall to be driven into the graphite energetically. Therefore, the only T_2 which will access the structure will be in the form of atomic or molecular species at very low pressure.

2.1.4.1 Tritium Retention ($70 K/y)

Various samples of C/C composites will be exposed to THO at 64 Pa and at different temperatures for varying times to determine the uptake and whether or not saturation occurs. Determining the amount of HTO in a sample is easy enough, but it is also important to determine how to get it out. These experiments will also include the release of HTO from the samples.

2.1.4.2 Radiation Effect on T2 Uptake ($30 K/y)

Radiation damage to the graphite structure may increase the HTO uptake by the graphite. Thus, irradiated samples of C/C composites will be exposed to HTO vapor at 64 Pa and at various temperatures and different dpa to determine if there will be an increase in the HTO uptake.

2.2 Fireballs and Chamber Dynamics ($550 K/y)

The rate that target chamber fireballs release their energy to the walls and whether fireballs preferentially propagate into transport paths are key critical issues for gas protection of target chambers. Experiments of relevant parameters need to be performed to study the gas-protection technique and the behavior of a fireball. This should be combined with computer simulations in order to confirm understanding of the relevant physics.

2.2.1 Fireball Experiments ($250 K/y)

A proper experiment must create a fireball with high enough energy density that it can make a transition from optically thick to thin and from supersonic to subsonic. Options include the use of the large Z-pinch machines (Z and SATURN) at Sandia National Laboratory, the Omega laser at the University of Rochester and the Nike laser at the Naval Research Laboratory. The Z machine is attractive because Z has a high temperature radiation produced and can most closely approximate the radiation coming from a burning target. A sketch of a possible experiment is shown in Fig. 4. Also, by producing 2 MJ of x-rays, Z and form a much larger or more supersonic fireball in a thicker sample of gas than the other facilities. The goals of these experiments would measurements of fireball propagation rates, shock strengths, and energy release rates in uniform gases that are laser IFE relevant and in gases containing laser paths.

2.2.2 Fireball Modeling ($250 k/y)

Radiation-hydrodynamics computer codes have been developed to model ICF targets and target chambers. These include 1, 2 and 3 dimensional codes developed at several institutions including LANL, LLNL, and the Universities of Wisconsin, California-Berkeley, and Rochester. Benchmarking should be performed for several codes. Radiation transport models and opacity and atomic physics models are the most likely areas that will need improvements. The SESAME equation of state and opacity data tables from LANL and the EOSOPA tables from the University of Wisconsin are good starting points. If molecular gases are envisioned, substantial improvements may be needed. The development of a new radiation-hydrodynamics code is not suggested because that is a very expensive and time-consuming job. The result of this project would be the testing of a number codes in the modeling of fireballs, the validation of some of these codes, and an understanding of mechanisms for controlling target chamber fireballs.

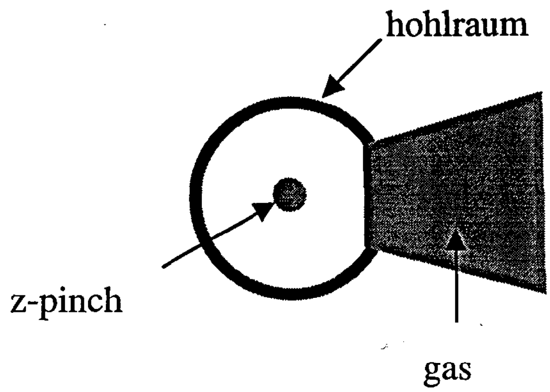

Fig. 4. Sketch of a Z fireball experiment.

2.2.3 Chamber Dynamics and Laser Propagation Simulation Tests ($50 K/y)

The major objective of this work is to develop the necessary capabilities to perform micro-chamber experiments in a 100-J class (or larger) laser facility. This includes developing the diagnostics and experimental techniques as well as designing the micro-chamber. Phase I subtasks include:

- Facility and diagnostic development
- Chamber designs
- Propagation studies
- Chamber response studies

Initial research efforts will utilize a Joule-class experimental facility (2–8 ns pulse-length Nd:YAG laser with harmonic generators to produce sorter wavelengths). Such a facility will allow us to develop the necessary diagnostics and experimental techniques without immediate need for a more expensive 100-J class laser facility. In addition, this facility can be used for fundamental studies of beam propagation, near surface physics, and selected chamber response issues. General shake-down of test chambers can be performed on this facility, thereby allowing us to obtain maximum value from the higher-yield tests.

Two chamber designs are planned: 1) a propagation test chamber and 2) a blast response test chamber. The propagation test chamber will be used to study laser beam characteristics as a function of the chamber environment. The response test chamber will be designed to reproduce a range of reactor-relevant phenomena using a 100-J energy source. This requires a chamber size of the order of 10 cm in diameter.

2.3 Final Optics Protection ($600 K/y)

The final optics for laser IFE (mirrors, diffraction gratings, or refractive wedges) are in the direct line of sight of the target. The final optics must, therefore, be protected from or be able to withstand the damaging effects of x rays, debris, and neutrons emitted by the fusion pulse. Fast closing shutters (closure time of about 0.1 ms) can stop slow moving debris (such as liquid droplets). A tenth of a Torr-m of gas, such as Kr or Xe, can stop fast vapor and very small droplets from reaching the final optics, and a few Torr-m will strongly attenuate x rays preventing surface damage. Two main alternatives for IFE final optics have been proposed: hot fused silica (gratings or wedges) and grazing incident metal mirrors (GIMM). Both approaches put a dogleg in the beam path and thus remove optics further upstream from direct line of sight of the target. Final optics made of fused silica would be operated hot (~400°C) to allow continuous annealing of radiation-induced color centers. Predictions are that the fused silica could remain adequately transparent for an acceptably long time under these conditions. GIMM and grazing incidence liquid metal mirrors (GILMM) are also expected to be robust (i.e., long lasting) against neutron damage and to some extent x-ray damage. The GILMM flows a self-healing, thin film (100 μm thick) of liquid metal such as Na along a flat inclined plane.

Development and demonstration of adequate life of final optics is a critical issue for laser IFE. If the lifetime is too short (perhaps less than a year), the change-out costs could be prohibitively high, and the resulting down-time could significantly reduce the plant availability.

2.3.1 GIMM / Neutron Damage ($150 K/y)

Grazing incidence metal mirrors (GIMM) were chosen for past laser IFE designs. The basic feasibility of the GIMM needs to be tested at DPSSL and KrF wavelengths at prototypical intensities. There is concern that a surface imperfection of about 1 μm in size "looks" locally like normal incidence and the damage limit is far exceeded and the imperfection will grow quickly to catastrophic failure of the mirror. In addition, surface imperfections caused by neutron damage may also affect reflectivity. Therefore, we propose that mirror samples be exposed to neutron fluence and re-tested for performance.

2.3.2 Fused Silica Radiation Damage ($150 K/y)

(Note: The estimated cost of this task far exceeds the $150K/y allocation; it is likely in the range of $500-800K/y. Additional resources from the OFES materials program would be sought for the majority of the work).

Over the past several years there has been some experimentation on fused silica final optics. Neutron and gamma exposure indicate that they are adequate for NIF operation. Theoretical modeling of the radiation damage mechanisms provides an estimate of the required operating temperature to allow continuous annealing. Because of strong absorption peaks near 240 nm, fused silica is not suitable for use with the KrF laser.

Experiments are needed to calibrate models for degradation of final optic materials. We expect to utilize LANSCE which is available for minimal yearly cost on a ride along basis with other experiments. Various steps can be taken to optimize LANSCE for these experiments. For example, samples can be resistively heated to elevated temperatures to simulate the effects of the radiation dose on sample heating, and the neutron spectra can be moderated to produce the exact He production to displacement ratio. Using these approaches at LANSCE, we have previously irradiated a few samples to ~1 dpa over a 9 month period. This is clearly below that expected at end of life for fusion facility but should allow us to test 0.1 - 1 year lifetimes for optics. The modeling effort described above will clearly be critical for extrapolating to the lifetime of final optics, hopefully greater than 1 year, but most likely less than the 30 year lifetime of power plants.

In the process of conducting our previous studies on irradiated NIF final optics described above [Marshall et al., Inertial Confinement Fusion Annual Report, UCRL-LR-105821-96, p. 61], it was determined that there were several synergistic but distinct physical effects of various types of radiation on the optical samples. For example KDP crystals were found to be optically sensitive only to gamma rays while fused silica glass was determined to be sensitive to both gamma and neutron irradiation that was dependent on the order of the irradiations due to a multi step damage mechanism. This detailed understanding was critical in developing models for end-of-life performance. It is anticipated that such effects will also be important for doses relevant to fusion power plants. Consequently we propose that gamma ray studies be performed separately without neutrons, for example on the LINAC at LLNL.

Tasks
- Identify and acquire attractive optical materials for radiation testing as potential final optics
- Develop Monte Carlo atomic damage models for candidate final optic materials
- Develop model to predict optical effects of MeV gamma-radiation to suggest final optic candidates
- Conduct irradiation experiments at LANSCE to evaluate radiation hardness
- Analyze run results; evaluate optical and mechanical properties to identify suitable final optic material
- Conduct gamma-irradiation experiments
- Analyze runs results; evaluate optical and mechanical properties to identify suitable final optic material

2.3.3 Alternative Final Optics Protection ($100 K/y)
A recently proposed alternative to the GIMM is to add a thin flowing film to the GIMM making it a grazing incidence liquid metal mirror or (GILMM). The advantages are that surface tension produces an extremely polished surface which is self healing and the laser damage limit is much higher making for a smaller and less expensive mirror to handle the power. The issues with GILMM are: 1) producing a stable smooth thin flowing film; 2) verifying its high reflectivity at high intensity laser light; and 3) determining its robustness against vibration, repeated pulses of heat on the surface, x-ray bombardment, and radiation damage.

Analytical tasks include:
- Literature search
- Analyses of radiation damage to the GILMM
- Analyses of dynamic stability of the GILMM.

- Design study of GILMM, including a system study of best liquid metals, design of the substrate, support system, liquid metal pumping and filtering system all aimed at feasibility of the concept and rough cost estimate.

Experimental tasks include:

- Measure reflectivity of liquid metal at high intensity laser light and compare to theory.
- Vary intensity (J/cm^2, ~10 ns) until the surface is disrupted (ablated). This can be near perpendicular incidence on static liquid; mercury or Bi might be acceptable although alkali metal is in the end preferred.
- Produce stable thin film (~100 μm) flow down an inclined plane with alkali metal; sodium preferred, NaK possible, mercury or Bi alloy also possible but not for final GILMM, diagnose stability with low power laser to measure variation of angle on reflection of grazing incidence light (typically 85° incidence) or use interferrometric techniques.
- Repeat measurements with intense laser pulsed to 6 Hz to check reflectivity on surfaces previously hit. Thin flowing films might be produced in a glove box in small areas of dimension 100 mm. Later the size should be increased and lasers brought to the glove box or the apparatus moved to appropriate lasers.

2.3.4 Gas Protection / Shock Tube Experiments ($100 K/y)

Gas stopping of x rays and debris is an important topic for the feasibility of laser IFE since the final optics can be destroyed by a single burst of x rays. With enough gas to attenuate x rays (a few Torr-m), the laser light can be deflected by the variable index of refraction if the gas is turbulent. The presence of turbulent gas can effect focusing of the light just like a star "twinkling." Experiments are needed to prove out the concept of gas protection of optics.

The target chamber fill gas will experience a fireball that will preferentially propagate toward the final optics. The fireball will have launched a shock before it reaches the final optics. The strength of the shock will likely not be enough to damage the material, but it may lead to vibrations or miss-alignment. The re-radiated photons will heat the surface, but not melt it. Two-dimensional radiation hydrodynamics are needed to quantify the shock and radiant loading. Shock take experiments will study the response of a sample mirror to the shock and arrive at design solutions. The quality of the gas prior to the laser firing is also an important issue, which can be resolved with shock take experiments. The shock may become turbulent as it flows around beam ports and mirrors. Shock take experiments would measure this effect and suggest designs to minimize it.

The RHEPP facility, located at Sandia National Laboratories in Albuquerque, is capable of supplying IFE relevant ions for materials response studies. RHEPP is a high rep-rate (several Hz) ion diode that can accelerate many species to energies from a few 100 keV to a few MeV. The pulse width can be close to 1 μs and the fluence can be up to 10 J/cm^2. RHEPP has been used to study thermal damage, melting, and vaporization of materials with ions. RHEPP experiments would provide ion damage limits for first wall and final optic materials. RHEPP could also simulate thermal damage to first wall and optics materials from fireball photons.

2.3.5 RHEPP Experiments ($100 K/y)

It is presumed that the target chamber fill gas will protect the first wall, grazing incidence mirrors or fused silica optics from direct damage from target ex-rays and debris ions. It may be advantageous to laser transport or target injection to use the minimum density gas. Therefore, it is important to understand the limits of allowable ion damage to the fused silica, grazing incidence mirrors and first wall. Also, the gas will be heated, and therefore rarefied, along the beam path by the laser, so those ions will have a longer effective range along those paths.

2.4 Design Modeling and Systems Analysis ($250 K/y)

It will be important to integrate the results of the various IFE R&D activities to assure progress toward meeting Phase-I milestones and development of an attractive end product. These studies provide a vital component of the 2002 feasibility assessment by demonstrating integration of all target chamber design issues. The following near-term tasks are focused on these needs:

- Continue planning for IFE chamber/target technology area with focus on objectives, milestones, and deliverables for Phase-I R&D.
- Establish objectives and determine design requirements for future integrated systems in the IFE development plan including the Integrated Research Experiments (IREs), Engineering Test Facility (ETF), and Demonstration Power Plant (Demo). Develop metrics (e.g., cost of electricity for a power plant) for these facilities to aid decision making.
- Develop, improve, and exercise of systems models for IRE, ETF, and Demo including major subsystems (i.e., chambers, drivers, target fabrication).

Toward the end of Phase-I it may be appropriate to conduct a major power plant conceptual design study to account for the progress made not only on chamber and target technologies, but also on the driver technology and target design. The cost of such a study would far exceed the $250 K/y allocated to this area and would require support from the Driver Technology and Target Design elements of the IFE program.

IV. Safety and Environmental

Safety and Environmental (S&E) issues will be one of the key factors in the success of fusion energy. In order for fusion to achieve its full potential for S&E advantages, it is essential that analyses are performed early in the design of any facility so that wise choices can be made and that lessons learned from previous designs are incorporated. It is also crucial that interactions between the different S&E areas are included, understood, and used to the greatest possible extent.

IV.1 Critical Issue for Safety and Environmental

The key issue in the S&E area can be summarized as follows:

- *Safety and Environmental.* Improved power plant designs that meets the "No-Public-Evacuation-Plan" criteria are needed; tritium containment and tritium inventory concerns must be resolved; end-of-life materials processing (recycling and radioactive waste disposal) must be acceptable.

The specific details for heavy ion and laser IFE are somewhat different, but this simple statement of the key S&E issue applies to both.

IV.2 Tasks and Cost for Safety and Environmental R&D

Required tasks and estimated costs in the S&E area are listed in Table 5.

Table 5. Tasks and Costs for Safety and Environmental R&D

Area / Task	FY00 ($K)	FY01 ($K)	FY02 ($K)	Lead / Support (fraction of total)
3.0 Safety & Environmental R&D	*700*	*700*	*700*	
3.1 Chamber Accident Analysis	100	100	100	LLNL(0.8) / INEL(0.2)
3.2 Materials Mobilization Expts.	200	200	200	INEL(0.8) / LLNL(0.2)
3.3 Dust / Aerosol Transport Modeling	100	100	100	UW(0.5) / Comp.
3.4 Accident Consequences	100	100	100	LLNL(0.5) / Comp.
3.5 Waste Management / Reduce Inventory	100	100	100	LLNL
3.6 Improve Safety Design	100	100	100	LLNL(0.5) / Comp.

*Comp. indicates tasks for competitive bid

IV.3 Phase-I Deliverables for Safety and Environmental R&D

The Phase-I deliverable for this work is:

- Chamber designs that meet the no-public-evacuation criterion, minimize radioactive waste volume and intensity, and limit the routine release of radioactive inventories to acceptable levels.

Achieving this will require:

- Improved data on important radionuclide release fractions (including hohlraum materials)
- Measurement of tritium inventories in high temperature C-C composites (laser chambers)
- Creation and validation of dust/aerosol transport models
- Updated safety analyses using estimates for accident temperature excursions and new radionuclide release data.
- Identification of methods to control and remove coolant impurities (target-debris and corrosion products) for liquid wall chambers
- Tritium recovery and control methods (compatible with the chamber structure material and plant designs)
- Identification of methods for recycling and/or clearance of activated materials
- Improvements in overall safety and environmental characteristics of current chamber/plant designs

IV.4 Summary Description of Safety and Environmental Tasks for Phase-I

The S&E work includes the development of tools applicable to both laser and heavy-ion fusion and analyses specifically tailored to the different chamber concepts and their issues.

3. Safety and Environmental R&D ($700 K/y)

3.1 Chamber Accident Analysis ($150 K/y)

Credible accident scenarios need to be developed for IFE power plants and target fabrication facilities. Previous work has done little more than calculate adiabatic temperature rise or use oversimplified arguments for estimation of maximum release fractions. This previous work is inadequate and would not hold up to external review. Assumptions have been unacceptably conservative (due to the lack of actual data) in some analyses and unrealistically optimistic and simplistic in others. The use of detailed accident scenarios and three-dimensional heat transfer models needs to be coupled with experimental data for key materials. These items cannot be supplanted by simple analyses. Work will focus on dry-wall and liquid chamber accident analyses. Credible accident scenarios will also be developed for the target recycling and fabrication facility.

3.2 Materials Mobilization Experiments ($200 K/y)

Recent oxidation-driven mobilization experiments performed at INEEL have produced data that now can be used to obtain better estimates of radionuclide release fractions during an accident. The experiments include exposures of key materials to air and steam environments at elevated temperatures as would be experienced during a severe accident. Although only a limited number of materials (primarily those of greatest interest to ITER) have been investigated, the facilities are readily adaptable to consideration of materials of interest to IFE (e.g., carbon composites, silicon carbide, Flibe, etc.). Upcoming experiments will allow, for the first time, accurate calculation of radionuclide release fractions, and thus, accurate calculation of off-site population doses and accident consequences.

3.3 Dust/Aerosol Transport Modeling ($100 K/y)

Fragmentation of solid and liquid materials or vapor condensation into micron sized dust particles formed from impulse loadings generated during ICF target burn brings about the critical issue of dust transport and containment for the IFE program. Fusion target blasts and the required subsequent chamber venting between shots in ICF means that chemically and radiologically active dust particles in the chamber atmosphere will be transported through open coolant, beam, and diagnostic ports. Once dust sources are properly identified and characterized by experiment on facilities like Nova and NIF, computer codes such as MELCOR and others are well-equipped to study dust transport for long time scales (millisecond and up). Furthermore, at UW-Madison hydrodynamic calculations using TEXAS are under way to study short time-scale (microsecond) single shot dust transport out of the reaction chamber in ICF facilities. Supporting experimental work using the Wisconsin Shock Tube to benchmark the code is in progress.

3.4 Accident Consequences ($50 K/y)

The primary goal of accident consequence analyses is to integrate the findings of the accident scenarios with the materials mobilization data and dust/aerosol transport modeling to estimate radiation doses under accident conditions. Doses and the consequences of those doses will be calculated that will enable direct comparison of IFE hazards with those associated with fission and non-nuclear systems. Maximally exposed individual, site boundary doses, and population doses will be calculated using all available data. When adequate data is not available, conservative, yet realistic estimates will be used. Cancer fatalities will be expressed as a range that uses both the linear, no-threshold model and a more realistic estimate of the risks involved.

3.5 Waste Management and Updated Inventories ($100 K/y)

Previous S&E studies have striven to ensure that all waste from an IFE power plant may be disposed of via shallow land burial (SLB). Current waste management objectives emphasize reduction and recycling of wastes over the need to eliminate non-SLB waste. The public is not yet able to understand the differences between types of wastes. It does, however, find large quantities of waste unappealing. Previous work in the area of waste management will be revisited and updated to incorporate current thinking. Radionuclide inventories will be recalculated utilizing an updated inventory code, activation cross sections, decay data libraries, and improved schemes for accounting for the pulsed nature of the irradiation. Three-dimensional neutron transport models will be used to generate neutron spectra. Neutron transport and activation calculations will be expanded to include the components of the final focus system. Emphasis will be placed on reduction of waste volumes, remote and hands-on recycling, and clearance of slightly activated materials. Practical recycling processes will be considered and used to develop realistic dose rate limits for materials subject to each process.

3.6 Improve Safety and Environmental Performance ($100 K/y)

As is the case with engineering design, S&E analysis is an iterative process. Once undesirable portions of a design are identified, changes will be made and the analysis will be repeated. It is important to reevaluate all portions of a particular design as substitutions and modifications in one area likely will affect multiple results (e.g., a reduction in the accident doses may increase the waste management burden). Alternate materials and/or concepts may introduce additional credible accident scenarios or may result in the need for additional experimental data.

V. Target Technology

The Target Technology area includes target fabrication, injection and tracking. Various target designs for direct drive IFE are being considered, but in the near term, attention will be given to using foam to support the DT fuel and ablation layers. Various options for target injection are also under consideration, including gas guns and electromagnetic accelerators.

V.1 Critical Issues for Target Technology

The critical issues for target technology are summarized as follows:

- *Target Fabrication and Injection.* A low cost method of high rate manufacture of direct and indirect drive targets with required precision is needed; target must survive mechanical and thermal loads during injection; accurate injection and tracking through post-shot chamber conditions is needed.

V.2 Tasks and Cost for Target Technology R&D

Proposed tasks and costs in the target technology area are listed in Table 6.

Table 6. Tasks and Costs for Target Technology R&D

Area / Task	FY00 ($K)	FY01 ($K)	FY02 ($K)	Lead / Support (fraction of total)
3.0Target Technology R&D	*2900*	*3100*	*3500*	
3.1 Target Fabrication	*1400*	*1500*	*1700*	
3.1.1 Assess Target Designs	150	100	100	LANL
3.1.2 Investigate Matls & Manufact. Tech	750	600	600	LANL
3.1.3 Dev Man Process for Fab/Fill/Layer	500	800	1000	LANL(2/5, 3/8, 3/4)/GA(balance)
3.2 Target Injection	*1500*	*1600*	*1800*	
3.2.1 Thermal Response	200	200	200	LANL
3.2.2 Injection accuracy & Tracking	650	625	650	GA
3.2.3 Acceleration Response	650	625	650	GA
3.2.4 Property Measurements		150	300	LANL

* Can use common experimental equipment for both heavy-ion and laser IFE targets

V.3 Phase-I Deliverables for Target Technology R&D

Target Fabrication (Applies to both laser and heavy ion fusion).

- Assessment of target fabrication needs and identification of most promising designs
- Development and testing of foam materials, barrier layers, and high-z coating processes
- Evaluation and recommendations for scalable manufacturing techniques for direct and indirect drive targets
- Experiments on fuel layering inside overfilled foam shells
- Evaluation of material properties at cryogenic temperatures (DT and other target components)
- Study on permeation filling vs. cryogenic injection filling

- Fill facility concept and required tritium inventory for each target design
- Radiation damage data for membranes and foams
- Demonstration of filling and layering of target concepts

Target Injection and Tracking (Applies to both laser and heavy ion fusion).

- Construction of a more capable injection system
- Demonstration of ability of cryogenic hohlraums to withstand accelerations
- Measurements of DT ice strength and predictions of acceleration effects on targets
- Measurement of thermal radiation effects on DT filled and layered cryogenic targets
- Modeling of target chamber gas effects on target injection
- Demonstration of hitting an indirect drive target on the fly
- Demonstration of injection and tracking of direct drive targets

V.4 Summary Description of Tasks for Target Technology for Phase-I

Significant overlap exists in the required R&D for target technologies (fabrication, injection and tracking) for laser and heavy ion IFE. Therefore, the target technology work is treated as an integrated R&D effort as reported here.

4. Target Technology R&D (FY00: $2900K, FY01: $3100K, FY02: $3500K)

4.1 Target Fabrication (FY00: $1400K, FY01: $1500K, FY02: $1700K)

Inertial Fusion Energy cannot become a reality unless fusion targets can be produced at the required rate, with high precision, and at reasonable cost. This includes manufacture of the target components (capsules and hohlraums), filling of the capsules, layering of the fuel and delivery of the assembled target to the injection system. Inertial Confinement Fusion (ICF) target designers have the freedom to propose target designs without cost being an over-riding concern. IFE targets, however, must be designed with cost as a prime constraint. Not only must the cost of providing the target be reasonably low, but the details of the design can have far reaching impacts on the costs of the drivers, target chamber, filling and layering systems, and injection system.

This work addresses three concerns. (1) How can targets and target components be fabricated economically which meet the stringent requirements necessary for use in a high gain IFE power plant? (2) How can capsule filling and layering be accomplished in a cost-effective manner at the required rate? (3) What is the impact of target design decisions upon the remaining IFE power plant systems such as target injection and tracking? The goal of this task is to show by FY02 that a credible pathway exists for the successful development of low cost targets for IFE, and that target fabrication need not be an impediment to moving ahead towards an IFE Integrated Research Experiment (IRE).

The major issues for IFE are not currently being addressed by the baseline Inertial Confinement Fusion (ICF) Program nor are they on the critical pathway to ignition at the National Ignition Facility (NIF) at the level required by this program. Target manufacture requires material and processing technologies that are currently unavailable or not amenable to mass production. DT filling and layering is being studied but not with the emphasis on the mass production of targets and the associated ES&H concerns. Furthermore, the targets must be able to survive the acceleration and temperature changes seen during injection into the target chamber, which is not a problem for ICF or NIF.

The most promising direct drive target designs incorporate low-density foams, high-Z coatings and barrier layers. Unfortunately these materials have not been developed yet. Two of the three proposed direct-drive target designs (1) (see Fig. 5) for the power plant incorporate low density (10 mg/cc), small cell size (< 200 Å), carbon/hydrogen foams of which only a few candidates are currently available. None of these have been fabricated into capsules with suitable properties, geometries, and at the low costs needed for power plant applications. Barrier layers will have to be formed on the foams to prevent the escape of the DT during the fill and layering process. These barriers may contain high Z dopants at levels of up to 5 atomic percent. Target fabrication may be the limiting constraint on the success of some of the more promising capsule designs for this program.

The filling of foam targets with DT and creation of a uniform DT layer (i.e., layering) have been explored but not with suitable foam filled targets and not with the precision required by this program. Non-destructive fill technologies will have to be developed that will allow rapid filling of targets while minimizing tritium inventories at risk. The compatibility of target materials with tritium as well as the size of the associated tritium reservoir needed for mass production of targets will limit the time that can be spent on the filling and layering processes. The foam has to be completely filled and layered and the surface layer smoothness has to be determined to a degree greater than previously determined. Current optical techniques developed by the ICF Community should allow the studies to be carried out on new candidate foams in suitable geometries.

Material properties at low temperatures will be needed to determine the allowable stresses that can be imposed on the targets during the injection process. The target may need to be cooled to a temperature somewhat below the layering temperature to survive injection into the chamber. During this process materials may separate, surfaces may become rougher, and the target may become less symmetrical than is allowable for a high gain target.

Each of the areas (capsule manufacture, DT filling and layering, and survivability during injection) requires the development of new processing and characterization technologies that are not critical to ICF or to NIF. Target fabrication development for IFE should be seen as essential to the growth of IFE as an alternative energy source.

4.1.1 Assess Target Designs (FY00: $150K, FY01: $100K, FY02: $100K)

Determine target material needs for both direct (DD) and indirect drive (IDD) power plants. Visit LBNL and NRL and discuss most promising target designs. Report on available materials and their properties.

4.1.2 Investigate Target Materials & Manufacturing Technologies (FY00: $750K, FY01: $600K, FY02: $600K)

Produce foams for direct and indirect drive targets and provide samples for testing using available drivers. Fabricate thin films and barrier layers using chemical and physical vapor deposition technologies, incorporating high Z dopants. Investigate the manufacturing of Be and polymeric shells using drop tower and microencapsulation techniques. Explore the manufacture of hohlraums for the HI power plant.

4.1.3 Develop Manufacturing Processes for Fabrication/Filling/Layering (FY00: $500K, FY01: $800K, FY02: $1000K)

Design an experiment to study the cryogenic layering of overfilled transparent foams. Perform fill and layering of overfilled foam targets. Study permeation and fill technologies that can be scaled to the mass production of fuel pellets.

Working closely with designers of inertial fusion targets, current and proposed IFE target designs will be reviewed to gain an understanding of the essential elements required in high gain IFE targets. Target manufacturing techniques that have the potential for economical mass production of IFE targets will be investigated. The probable target cost and quality obtainable through scaling commercial fabrication techniques to the size and uniformity required of inertial fusion targets will be determined. The cost and quality of such targets will be compared and contrasted with the cost and quality of targets produced through scaling up the processes currently used to produce ICF targets. Both capsule and hohlraum production processes will be investigated as well as automated processes for assembling capsules into hohlraums. Techniques will be recommended that (1) have the potential for economic mass production, (2) have the promise to achieve the tolerances required, and (3) integrate self-consistently into an IFE target production-filling-layering-injection process. We will work closely with the other ICF/IFE target fabrication labs to carry out the fabrication technique development work needed to demonstrate that a credible pathway exists for fabrication of low cost, high quality targets for IFE.

Prototype IFE target components and targets will be fabricated by processes deemed suitable for mass production. The techniques to be emphasized will be those deemed most promising, considering the trade-off between production cost and target quality. Initially, the purpose of prototyping will be to determine, through measurement and characterization, the present limits of the proposed fabrication techniques and technologies. Later prototype targets will be provided to target injection and tracking experiments. Ultimately, prototype IFE targets will be fabricated for proof of principal experiments to be carried out at the National Ignition Facility.

The current ICF capsule filling technique (permeation fill) will be critically evaluated to determine whether it provides an economic solution to the requirements of IFE. Filling techniques proposed in previous IFE studies will be reviewed along with other possible techniques. Based on the then current IFE target designs, the materials involved, and the results of the filling studies, the lowest cost feasible IFE capsule filling techniques will be recommended for implementation.

The feasibility of employing the current ICF capsule layering techniques for IFE will be evaluated. The techniques proposed in previous IFE studies will be reviewed and their feasibility for the current IFE target designs will be determined. Other possible layering techniques will also be explored, for example, the possibility of layering of capsules in a fluidized bed will be considered.

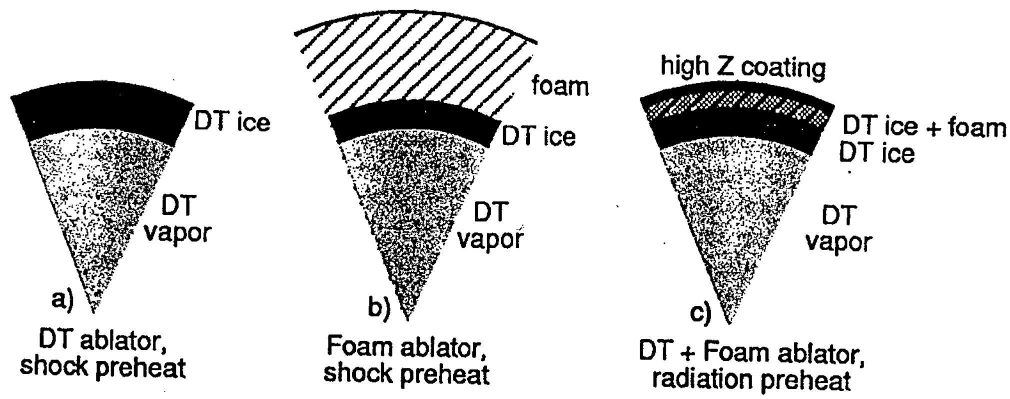

Fig. 5. Target designs for direct-drive IFE fuel capsules. (Bodner, S. E.; *et al.* "Direct -Drive Laser Fusion: Status and Prospects." Physics of Plasmas, 5(5), 1901-1918.)

4.2 Target Injection and Tracking R&D (FY00: $1500K, FY01: $1600K, FY02: $1800K)
A commercial IFE power plant must place about 430,000 cryogenic targets each day (assuming a rate of 5 Hz) into a target chamber operating at 500 - 1500°C. The only way to do this will be to inject the targets into the target chamber at high speed, track them and hit them on the fly with the driver beams. This must be done with high precision, high reliability of delivery, and without damaging the mechanically and thermally fragile targets. Key components of demonstrating a successful IFE target injection methodology are:

1) Ability of targets to withstand acceleration into chamber
2) Ability of targets to survive chamber environment (heating due to radiation & gases)
3) Accuracy and repeatability of target injection
4) Ability to accurately track targets.

The ultimate goal of this development program is to provide a demonstration of successfully injecting a prototypical cryogenic target into a hot chamber representative of an IFE target chamber. However, the Phase I budget and time constraints dictate a dual approach to providing information for the decision to proceed with an IRE. This dual approach consists of (a) demonstrating processes and equipment at room temperature and (b) providing thermal and strength data to allow modeling of cryogenic performance. The proposed injection and tracking program addresses issues associated with both direct drive and indirect drive target designs. Work will be performed at General Atomics and at Los Alamos National Laboratory. The following items will be addressed by either analytical means or by demonstration by the end of Phase 1:

- target injection requirements including velocity needed
- design of sabots for direct drive targets and a sabot removal demonstration

- design concepts of an accelerator with a technology applicable to IFE power plant requirements
- effects of acceleration on the target structure, including measurements of DT ice strength data under representative conditions and demonstrating acceleration of cryogenic hohlraums
- a demonstration of the ability to inject direct drive and indirect drive targets at higher velocities than previously shown, and at the required accuracy
- a demonstration of providing tracking data for direct drive targets and for indirect drive targets at higher velocities than previously shown
- a demonstration of hitting an injected target on-the-fly with a low current ion beam, using information from the target tracking system (joint effort with driver beam personnel)
- a measurement of the effects of thermal radiation on the target and investigation of coatings and other means to protect the target
- analytical evaluation of the effect of target chamber gases on the target during injection

4.2.1 Target Thermal Response (FY00: $200K, FY01: $200K, FY02: $200K)

The heat load to the target during injection is composed of thermal radiation and heating by target chamber gases. The issue of thermal radiation exposure during injection is a matter of exposure time to the high temperature radiation. It is not necessary to have a target in motion to determine this effect. Instead, a target will be held in a stationary configuration, filled and layered, and exposed to high-temperature thermal radiation. The effects on the target will be observed to determine its degradation with time. With this approach, target materials can be exposed to the environment for short times and then be removed from the cryostat for post test characterization.

A computational fluid dynamic code will be used to model and analyze the effect of target chamber gases on the injected target. Data on the fluid properties of the chamber atmosphere and the thermal properties of the target will be used. The heat flow into the target will be calculated and aerodynamic considerations such as drag will be analyzed.

4.2.2 Target Injection Accuracy & Tracking (FY00: $650K, FY01: $625K, FY02: $650K)

These issues will be addressed with experimental demonstrations. First, existing gas gun injection equipment that has been used to demonstrate the accuracy of injection of indirect drive targets will be utilized to investigate direct drive targets and sabot removal effects. Secondly, working with driver beam personnel and the existing equipment, a demonstration of hitting a hohlraum during injection will be carried out. This demonstration will consist of hitting a scintillator-coated hohlraum with a low current ion beam, to show how beam steering can correct for random target placement uncertainties, as controlled by the optical tracking system.

A new more capable injector (based on accelerator technology) will be constructed and utilized to demonstrate higher velocity direct drive injection and indirect drive injection and measure the accuracy of placement. This injector will be selected based on a review of current technologies so that it is upgradeable to IFE power plant specifications (scale and rep-rate). It will be upgradeable to a multi-shot burst capability. The accelerator will be utilized to measure accuracy with simulated cryogenic targets during Phase I. This accelerator-based injector will be designed for later (Phase II) interfacing with cryogenic permeation fill and transport systems for a full, cryogenic injection demonstration into a high-temperature chamber by the end of FY05.

4.2.3 Target Acceleration Response (FY00: $650K, FY01: $625K, FY02: $650K)

It was assumed in the SOMBRERO design that the target could be injected at ~4K and could heat up to 18.5K during its transit across the chamber (at about 150 m/s). Recent work by LLNL indicates that a layered target can only sustain a temperature change of ~0.5K without increases in ice layer roughness that degrade target performance significantly. One solution to this narrowed requirement on target heating is a much higher injection velocity (~2000 m/s). This can result in a need for target accelerations exceeding 1000 g's. While tradeoffs on target surface emissivity, accelerator length, and potential target protective methods need to be evaluated, the limitations on fuel temperature increase will likely result in higher forces than previously assumed during the injection process.

The technical approach chosen for the target acceleration response is to measure target material properties under representative conditions (as described in Section 3.2.4) and to analytically evaluate stresses imposed on target structures. Finally, a demonstration of accelerating indirect drive target hohlraum assemblies (with simulated fuel capsules) will be carried out at cryogenic temperatures. This demonstration will be done utilizing the accelerator described in Section 3.2.2.

4.2.4 Target Property Measurements (FY01: $150K, FY02: $300K)

The technical approach chosen for direct drive targets is to carry out measurements of the strength of DT ice under the temperature conditions of target injection. The currently available data indicate acceleration forces near 1000 g's may be acceptable. However, these data are measured with deuterium at 16.4K and no data are available for DT ice at 18.5K. Indeed, the properties are changing rapidly in this temperature range because it is very near the melting point, and the strength may be a function of time due to buildup of He-3 from tritium decay. Thus, measurements of DT ice strength will be carried out and coupled with analytical evaluations to calculate the acceleration stresses imposed and the DT ice survivability. In subsequent years, a full demonstration program of cryogenic target injection will be carried out. This issue is much less critical for indirect drive targets since the presence of the surrounding hohlraum provides thermal radiation protection which results in significantly lower injection velocities and accelerations. Additional material property measurements will be carried out as needed and analytical evaluations will be used to address stresses imposed on structures other than DT ice within indirect drive targets.

Subtasks include:

- Measure the physical properties of target materials that will affect survivability of targets during the insertion process.
- Determine thermal and mechanical properties as well as tritium compatibility of target materials.
- Observe the behavior of solid DT below 10K. (i.e., can a DT solid layer be cooled below 10K without forming cracks or pulling away from the capsule inner surface. How does foam affect this behavior?)

VI. Phase-I R&D Cost Summary

Table 7 combines the costs of the Tables 2, 4, 5 and 6 in a top-level summary. The cost estimates for these tasks described in Sections II-V were made by the authors assuming a budget limited funding scenario. The proposed total of $7.2M in FY00 includes $1.8M for laser fusion chambers, $1.8M for HIF chambers, $0.7M for safety and environmental, and $2.9M for target technology. That target technology component is planned to increase somewhat in FY01 and FY02.

Table 7. Summary of IFE Chamber and Target Technology R&D Costs

	FY00	**FY01**	**FY02**
Area	($K)	($K)	($K)
1. Heavy Ion Fusion Chambers	1800	1800	1800
2. Laser Fusion Chambers	1800	1800	1800
3. Safety and Environmental	700	700	700
4. Target Technology	2900	310	3500
Total	**7200**	**7400**	**7800**